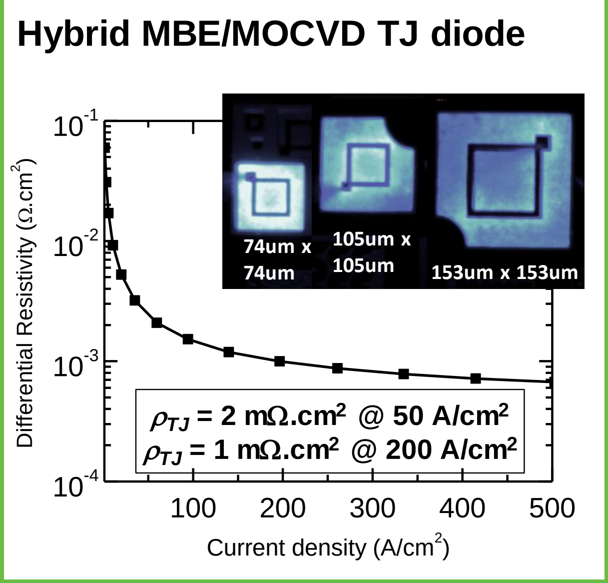
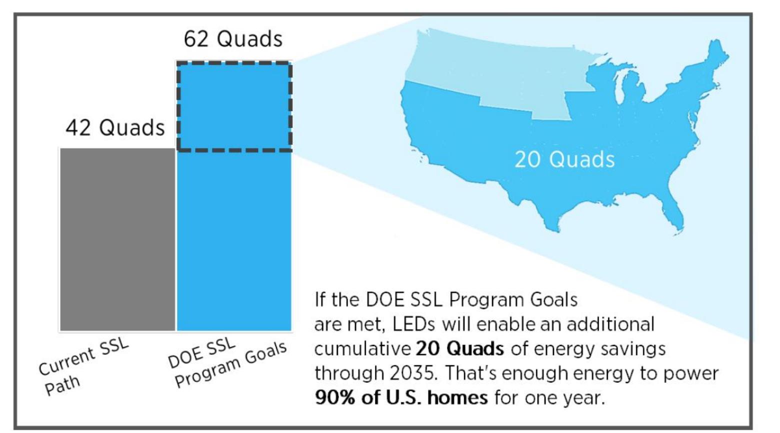
Tunneling-Enabled High-Efficiency High-Power Multi Junction LEDs





Sandia National Laboratories and Ohio State University
Andrew Armstrong, Sandia National Laboratories
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Project Summary

Timeline:

Start date: 10/1/2018

Planned end date: 9/30/2020

Key Milestones

1. Demonstrate TJ on MOCVD LED; 7/2019
2. Demonstrate 2x TJ-LED; 3/2020
3. Demonstrate droop-free 3xMJ-LED; 9/2020
4. External validation of MJ-LED performance; 9/2020

Key Partners:

Sandia National Laboratories
Ohio State University
Lumileds

Budget:

Total Project $ to Date:

- DOE: $250,000
- Cost Share: $0

Total Project $:

- DOE: $1,000,000
- Cost Share: $0

Project Outcome:

Demonstrate tunneling-enabled, multiple active region light emitting diodes (LEDs) that circumvent efficiency droop by operating at three times the input electrical power at the same wall plug efficiency as a conventional LED. For a tunnel junction resistivity < 1 mOhm.cm^2, multi-junction LED performance is equivalent to a conventional LED that maintains > 98% relative EQE at 100A/cm^2 vs 35 A/cm^2, which surpasses the 2025 target for current droop described in the DOE Solid-State Lighting 2017 R&D Plan.

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Team

Sandia National Laboratories

Dr. Andrew Armstrong (PI)
- Team coordination
- Device design
- 12 yrs experience GaN LED characterization

Dr. Brendan Gunning
- MOCVD crystal growth
- 6 yrs experience GaN MBE crystal growth
- 3 yrs experience GaN MOCVD crystal growth

Dr. Mary Crawford
- Optical (PL) and opto-electronic (EL, EQE) LED characterization
- 19 yrs experience GaN LED design, fabrication, and characterization
- 3 yrs experience commercial MOCVD GaN LED crystal growth

Ohio State University

Prof. Siddharth Rajan (co-PI)
- MBE GaN crystal growth
- Device design and fabrication
- 20 yrs experience GaN MBE crystal growth
- 6 yrs experience in III-nitride TJ and TJ LED growth and characterization
- Rajan group has ## publications on III-N TJ and TJ-LEDs

Prof. Jinwoo Hwang
- TEM characterization
- 8 yrs experience in GaN microscopy

Prof. Shamsul Arafin
- LED fabrication
- 11 yrs experience in III-V opto-electronics

Lumileds

Dr. Parijat Deb
- Guidance on commercial compatibility

Andrew

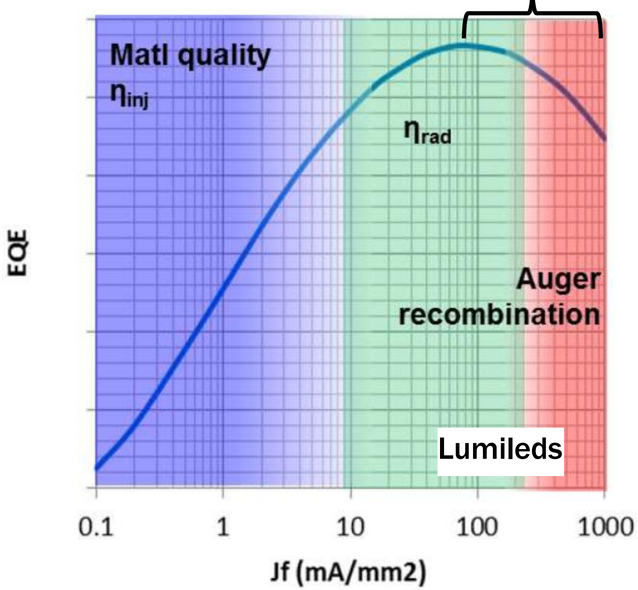
- ➢ Armstrong and Rajan have 9 publications together over the last 4 year
- ➢ 7 of those publications involve AlGaN TJ LEDs

Challenge: Must improve GaN LED efficiency

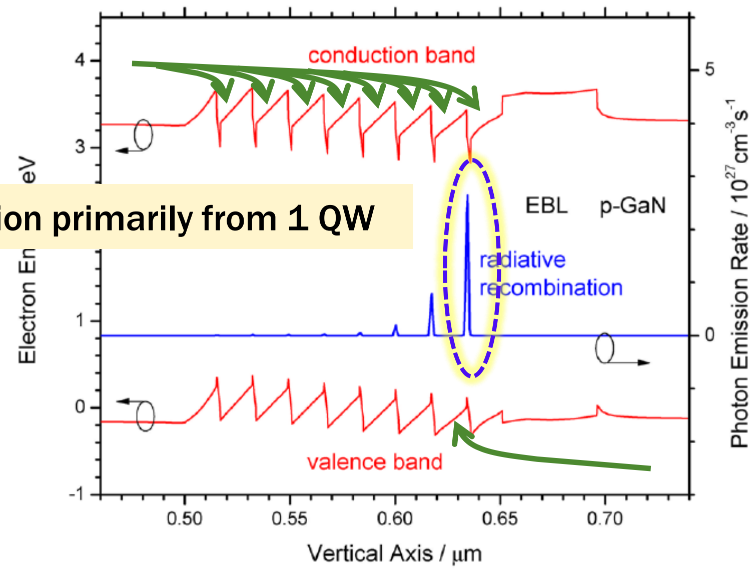
Problem Definition:

- DOE 2030 goal of $40B/yr consumer savings due to solid-state lighting (SSL) requires increasing SSL market penetration
- Critical path is reducing consumer payback period by increasing SSL efficiency
- GaN LED efficiency primarily determines SSL efficiency
- “Efficiency droop” problem limits GaN LED efficiency far below fundamental limit
- Must solve efficiency droop to increase SSL efficiency and maximize consumer savings

“Efficiency droop” aka “current droop” occurs at high current density



Standard LED



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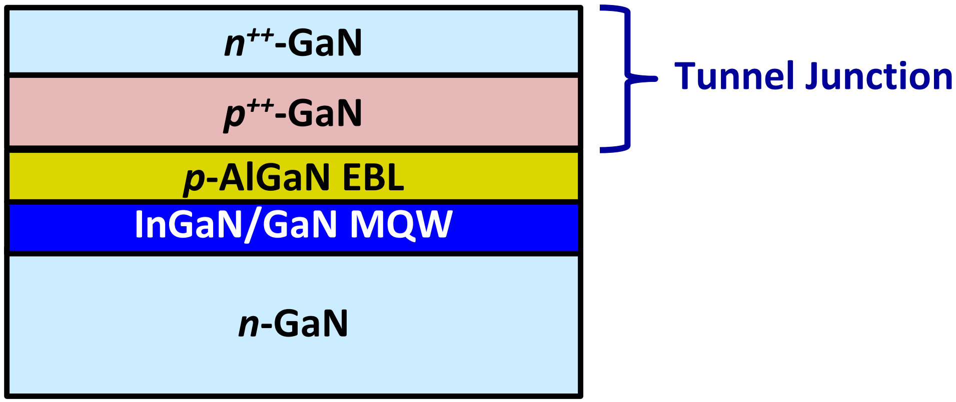
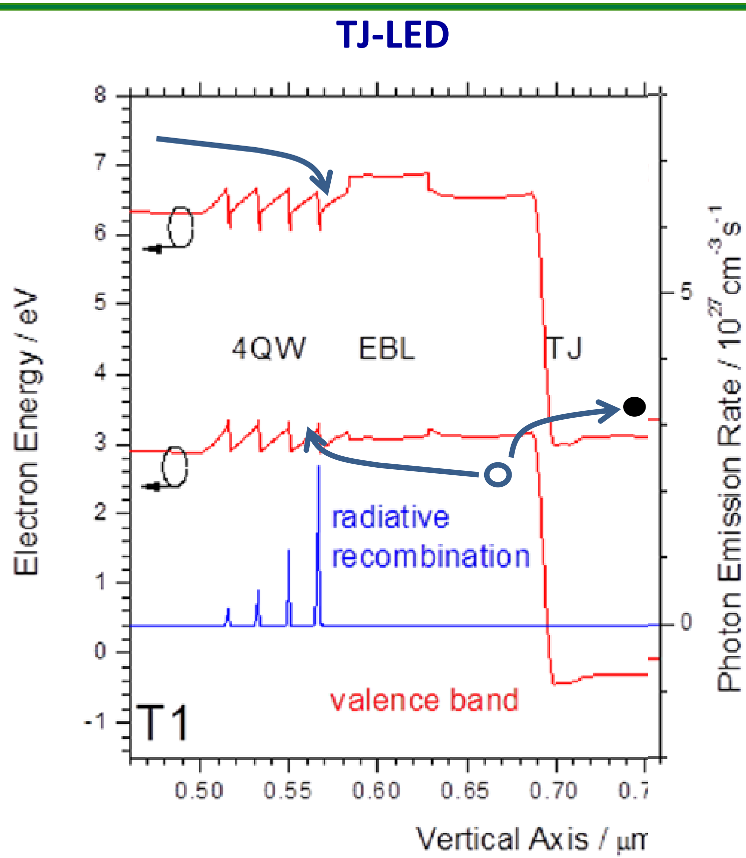
Piprek APL 104 05118 (2014).

Approach: Avoid efficiency droop using tunnel junction LEDs





Piprek APL 104 05118 (2014).

- Tunnel junction LEDs (TJ-LEDs) replace p-GaN contact with n-GaN contact[1]
- Electrons injected from the bottom n-type contact
- Electrons extracted by the top n-type contact → Holes injected by TJ

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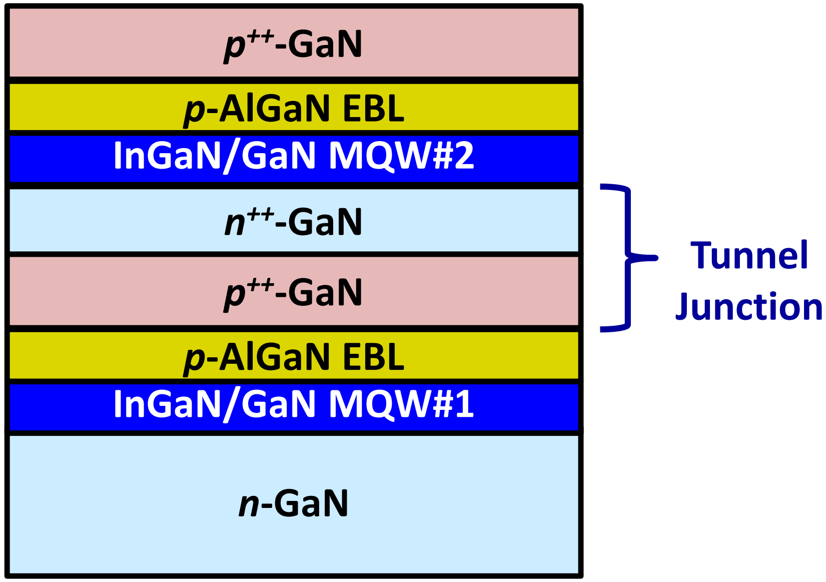
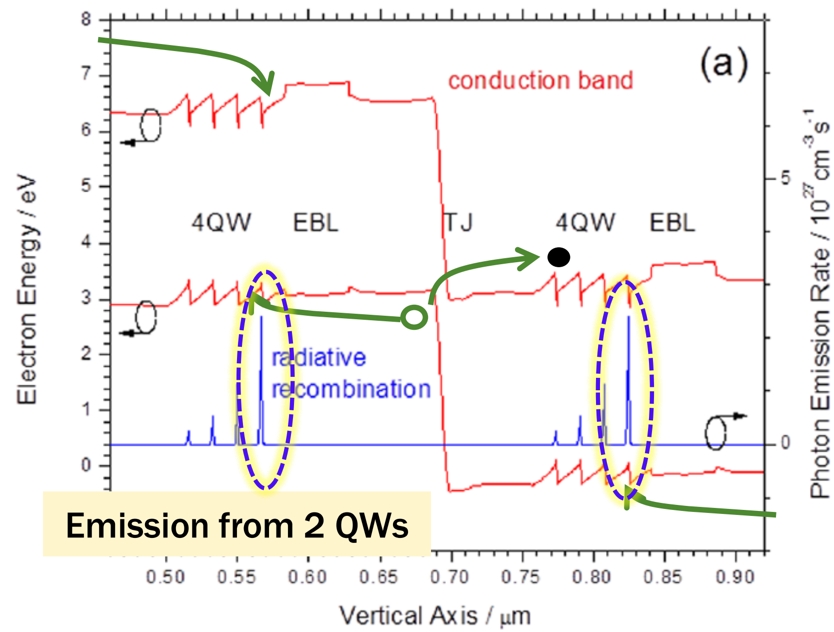
1. Jeon *et. al*., APL, 78,3266 (2001)

Approach: Avoid efficiency droop using tunnel junction LEDs



2x4 QW TJ-LED



Piprek APL 104 05118 (2014).

- ➢ Cascading multiple MQW regions with TJs can circumvent efficiency droop[1]
- ➢ TJ injects holes into MQW#1 and top contact injects holes into MQW#2
- ➢ **Twice the LED output power for the same input current**

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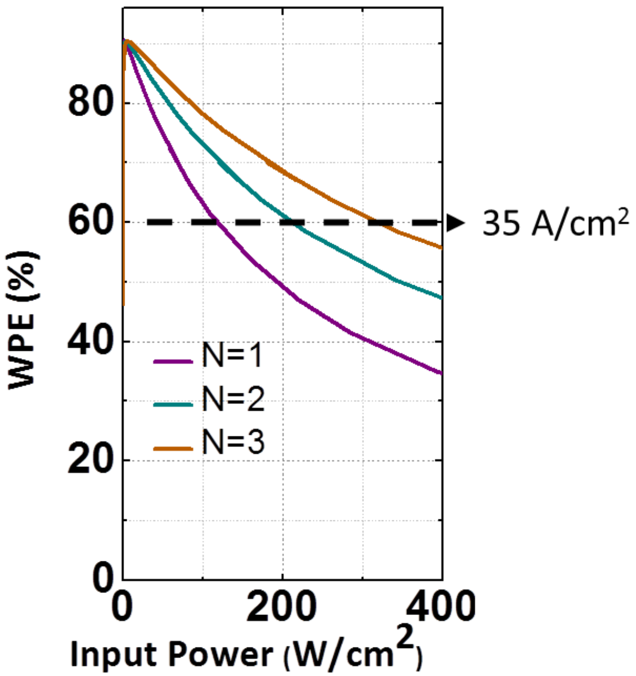
1. Akyol et al., APL 103 081107 (2013).

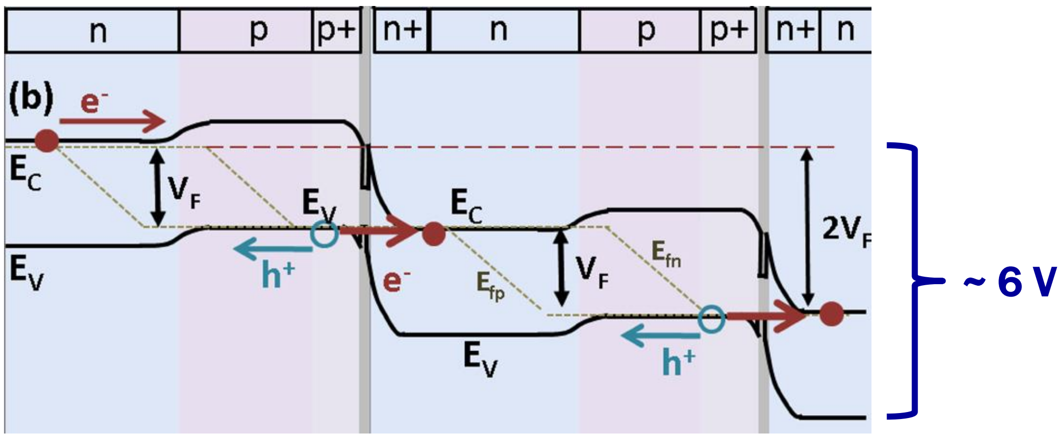
Approach: TJ LEDs multiply output power without reducing efficiency

WPE for cascaded TJ-LED



Akyol et al., APL 103 081107 (2013).

Higher operating voltage for cascade TJ-LED



Akyol et al., APL 103 081107 (2013).

- *Nx* multi-junction LED (MJ-LED) increases optical output power by ~*Nx*
- Current stays constant and therefore so does wall plug efficiency (WPE)
- Price is higher forward voltage, but increasing voltage does not reduce radiative efficiency

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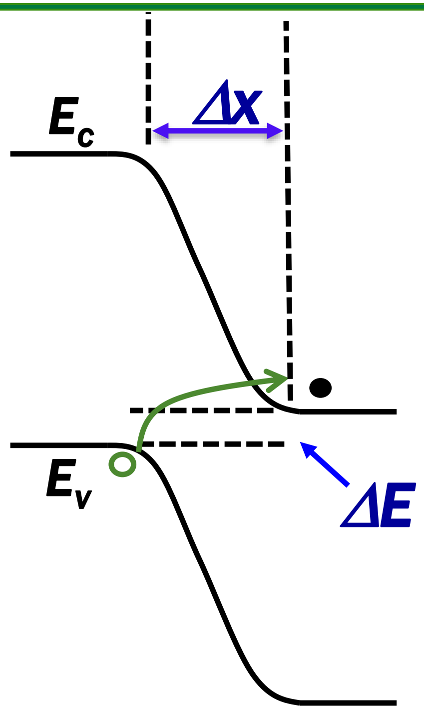
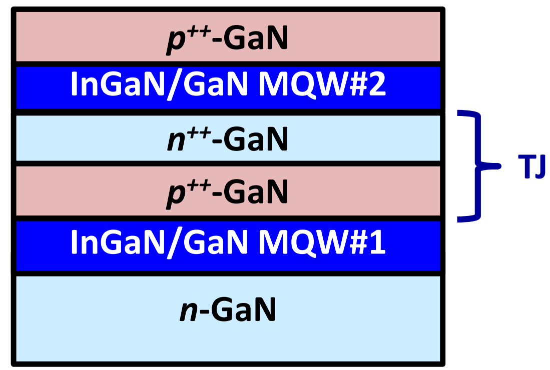
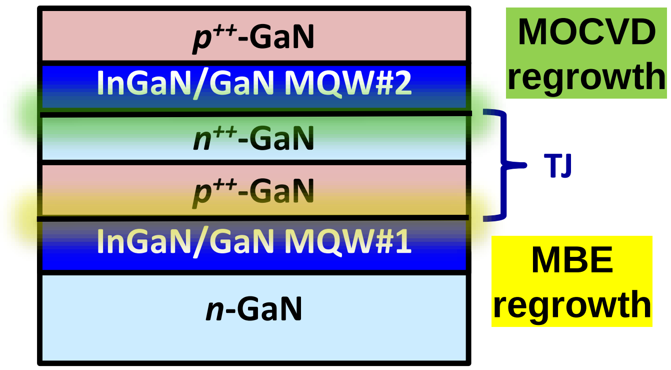
Approach: Minimize TJ voltage drop at low current



Approach 1: All MOCVD



Approach 2: MOCVD/MBE



- Require $\rho_{TJ} \leq 2$ mΩ.cm^2 at 50 A/cm^2 for < 0.1 V excess voltage drop in 2x MJ-LED
- High doping concentration: reduce energy barrier and reduce tunneling distance
- Best TJs grown by molecular beam epitaxy (MBE), but best LEDs grown by metal-organic chemical vapor deposition (MOCVD)

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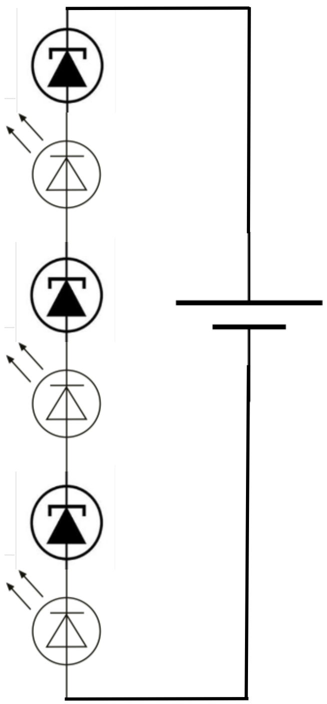
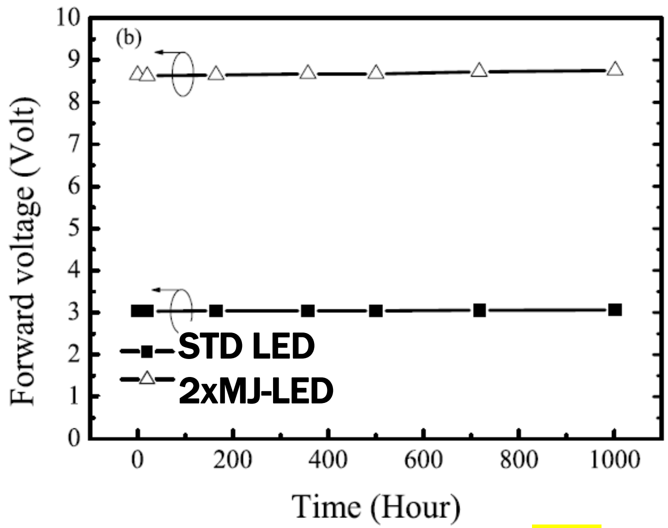
Approach: Differentiation from competing approaches

MJ-LED



MOCVD Cascade LED

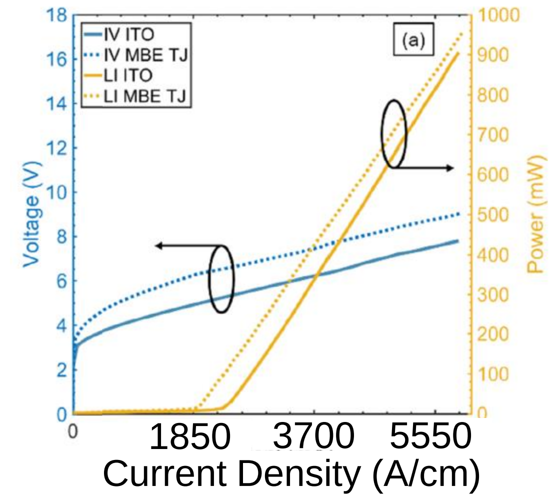


Chang *et al*., IEEE JQE 51 3300505 (2015).

High TJ resistance:

- Doping: [Si] < 10^{19} cm^{-3}
- Large forward voltage reduced WPE

MBE/MOCVD TJ laser



Hamdy *et al*., IEEE JQE 51 3300505 (2019).

Most work focused on TJ lasers:

- Single MQW region
- Much higher current density

- TJ-LED is a circuit solution to efficiency droop → universally applicable solution
- Agnostic to physical cause of current droop because device operates at low current
- Most effort focused on fixing “site-specific” LED problems (leakage, transport, defects etc.)

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Impact: Value proposition

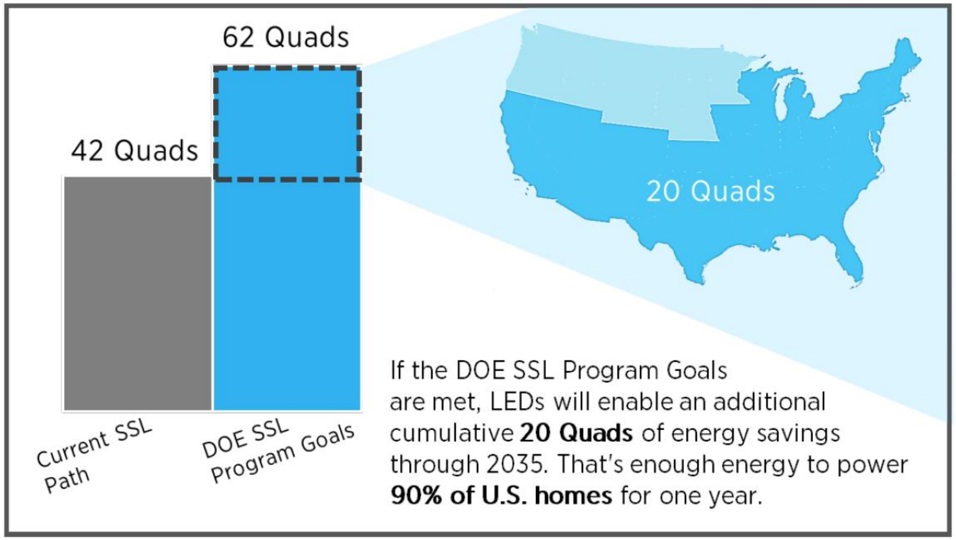

Figure 2.10 U.S. Cumulative Energy Savings Forecast from 2015 to 2035

Source: DOE SSL Program, "Energy Savings Forecast of Solid-State Lighting in General Illumination Applications," September 2016 [1]

- MJ-LEDs have potential to achieve the DOE SSL goal of 96% relative EQE at effective current density of 100 A/cm^2 (3xMJ-LED at 33 A/cm^2) *vs*. 35 A/cm^2 (standard LED)
- Accelerate progress toward DOE 2030 goal of $40B/yr consumer savings
- Increasing LED market penetration will foster domestic lighting manufacturing by enabling custom lighting solutions that take place near the end user
- Increasing LED efficiency enables new economic sectors, such indoor farming

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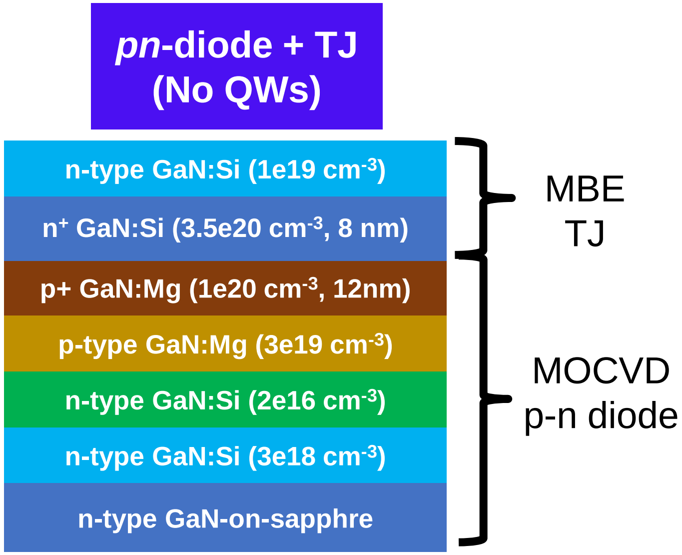
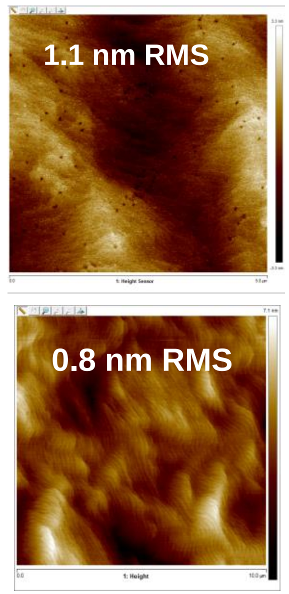
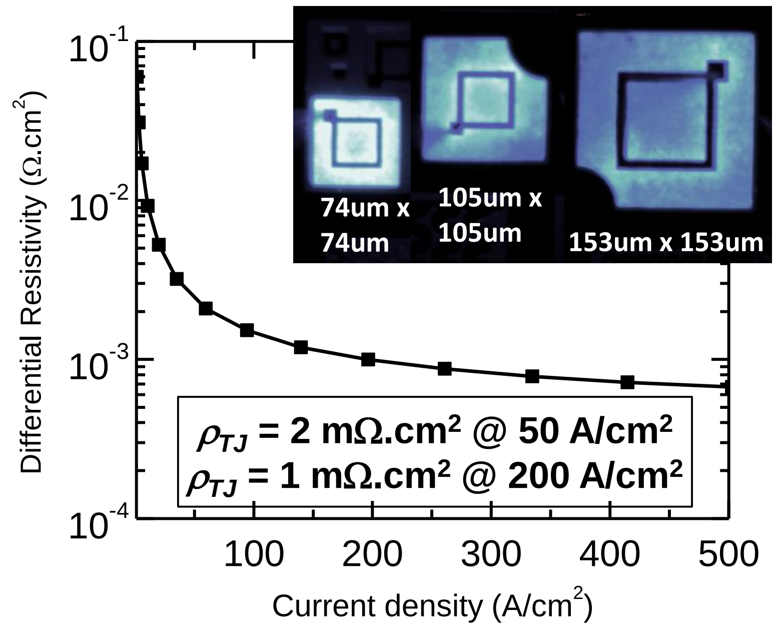
Progress: Execution against milestones



AFM



Hybrid MBE/MOCVD TJ diode



- First attempt at MBE/MOCVD TJ diode was successful
- Achieved target ρ_{TJ} for 2x MJ-LED
- Electroluminescence (EL) shows good current spreading

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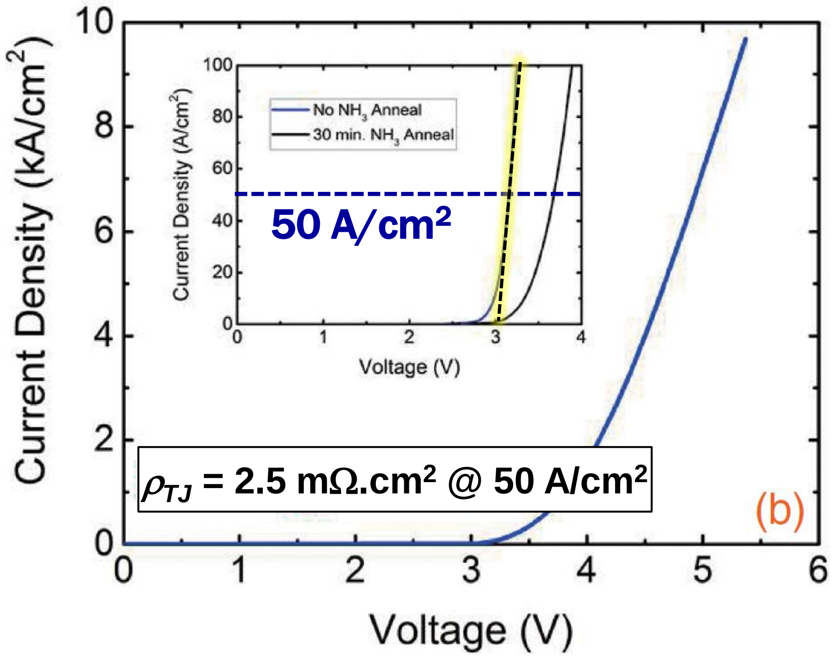
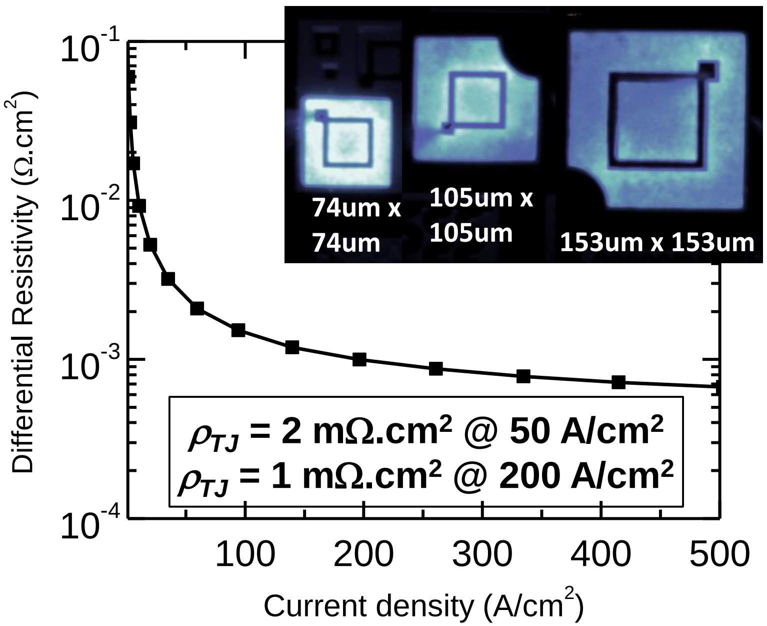
Progress: MBE/MOCVD TJ among better reported

MBE/MOCVD TJ *pn*-diode



Young APEx 9 022102 (2016).

Hybrid MBE/MOCVD TJ diode



➢ First MBE/MOCVD TJ comparable to top reports for low current density

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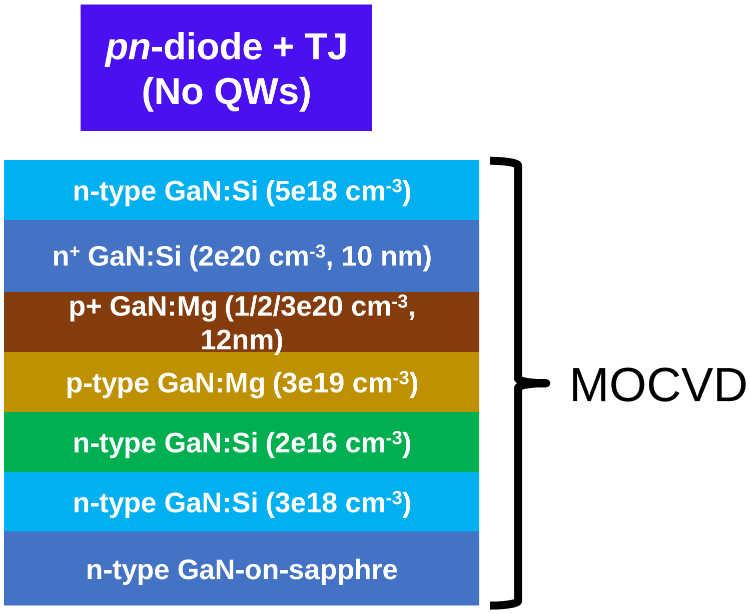
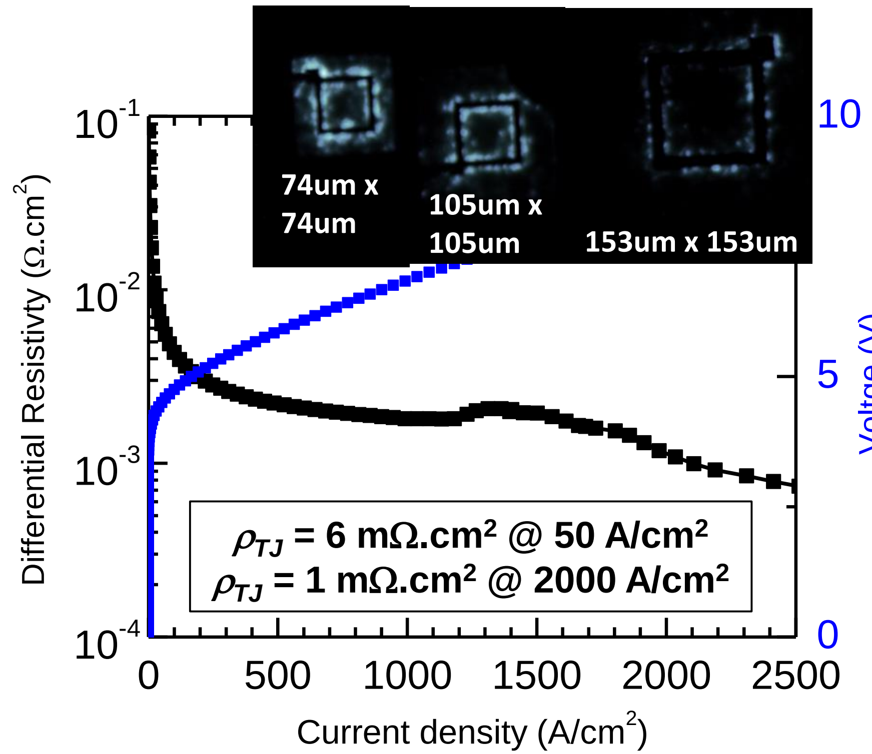
Progress: Execution against milestones



Electroluminescence and *IV*



- First MOCVD TJ diode was successful
- Higher ρ_{TJ} and less uniform EL compared to MBE/MOCVD hybrid TJ diode
- Likely due, in part, to insufficient Mg activation (equipment issue since solved)

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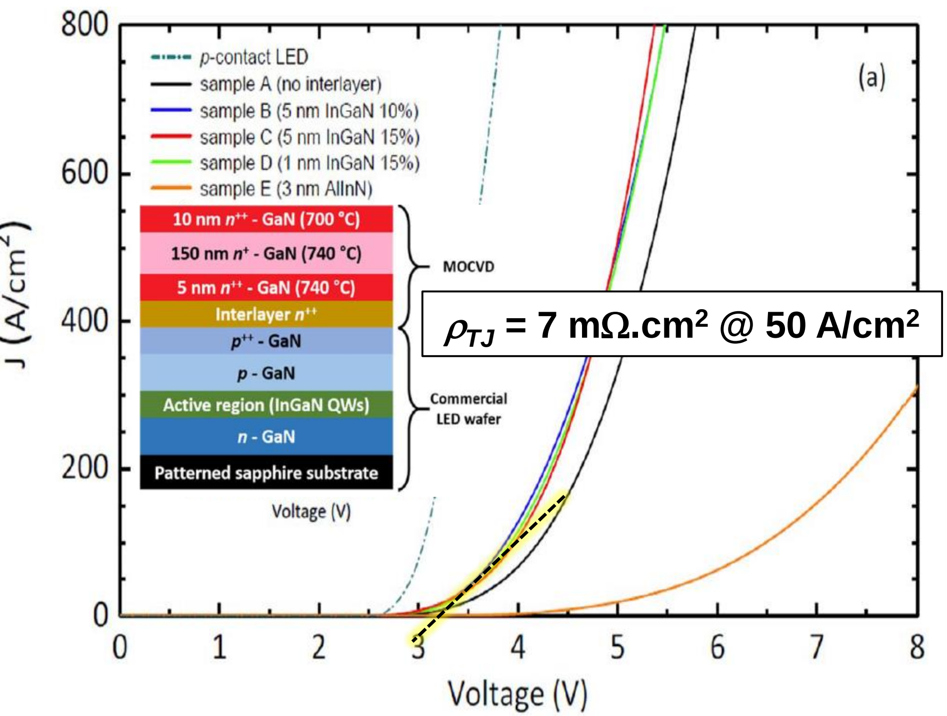
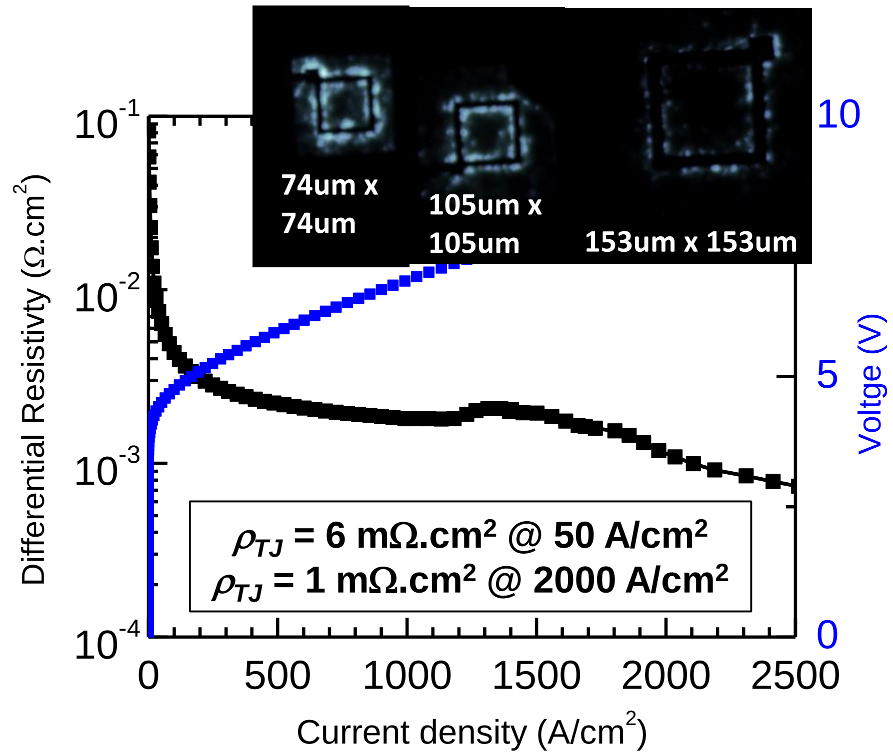
Progress: all-MOCVD TJ among better reported

All-MOCVD regrown GaN TJ-LED



Sohi SST 34 015002 (2019).

Electroluminescence and *IV*



➢ First all-MOCVD TJ comparable to top reports for low current density

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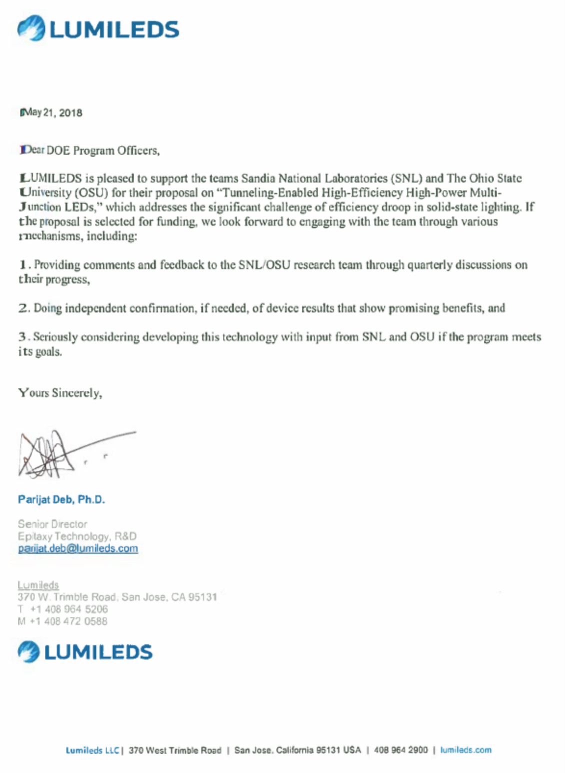
Stakeholder Engagement: Path to commercialization



LUMILEDS

May 21, 2018

Dear DOE Program Officers,

LUMILEDS is pleased to support the teams Sandia National Laboratories (SNL) and The Ohio State University (OSU) for their proposal on "Tunneling-Enabled High-Efficiency High-Power Multi-Junction LEDs," which addresses the significant challenge of efficiency droop in solid-state lighting. If the proposal is selected for funding, we look forward to engaging with the team through various mechanisms, including:

1. Providing comments and feedback to the SNL/OSU research team through quarterly discussions on their progress,

2. Doing independent confirmation, if needed, of device results that show promising benefits, and

3. Seriously considering developing this technology with input from SNL and OSU if the program meets its goals.

Yours Sincerely,

Parijat Deb, Ph.D.

Senior Director
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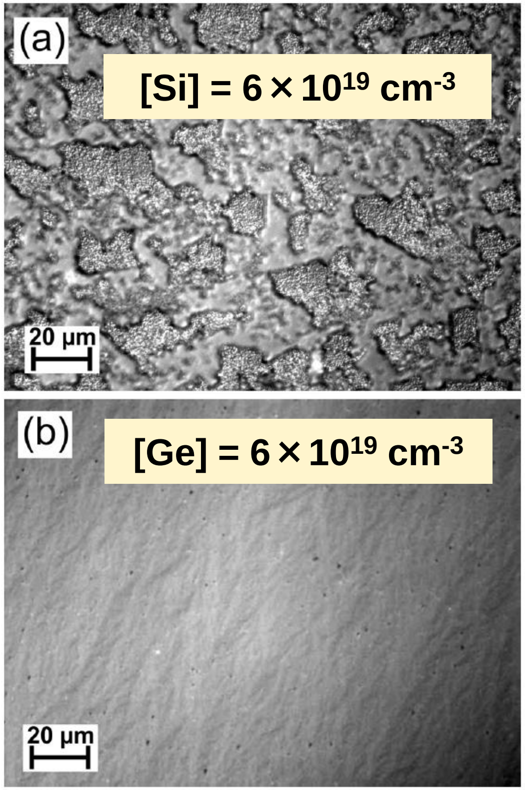
- Program is six months in to a 24 month project
- We are engaging directly with Lumileds, the leading SSL manufacturer for:
    1. Guidance on research directions with respect to manufacturability
    2. Independent confirmation of promising device results, as needed
    3. Consideration of technology development if MJ-LEDs meet the stated goals
- Both Sandia and Ohio State have large organizations dedicated to licensing technology and transitioning it to commercial partners

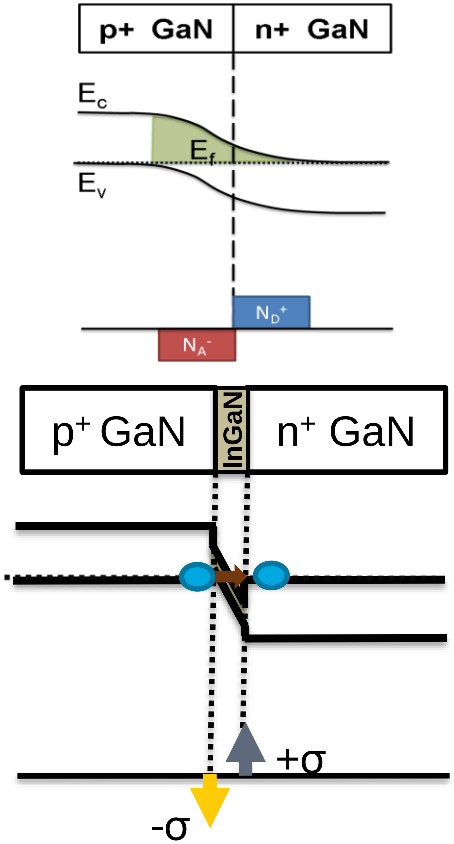
An

Remaining work: Improving TJ performance

MOCVD GaN morphology at high doping



InGaN interlayer for polarization doping

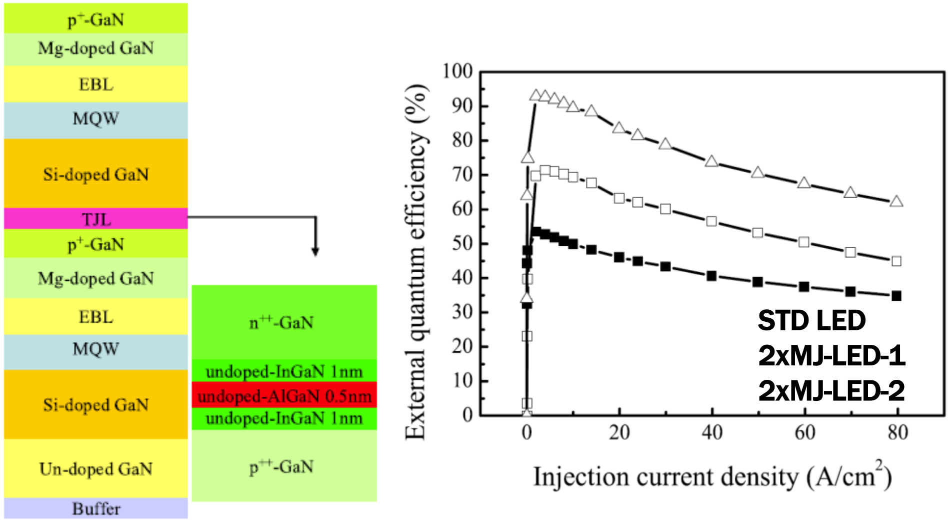


- ➢ Demonstrated working MBE/MOCVD and all-MOCVD TJ diodes
- ➢ Reduce MOCVD ρ_{TJ} by replacing Si with Ge dopant for higher doping levels
- ➢ Insert InGaN polarization-doping layers to increase doping (if necessary)

Andrew Armstr

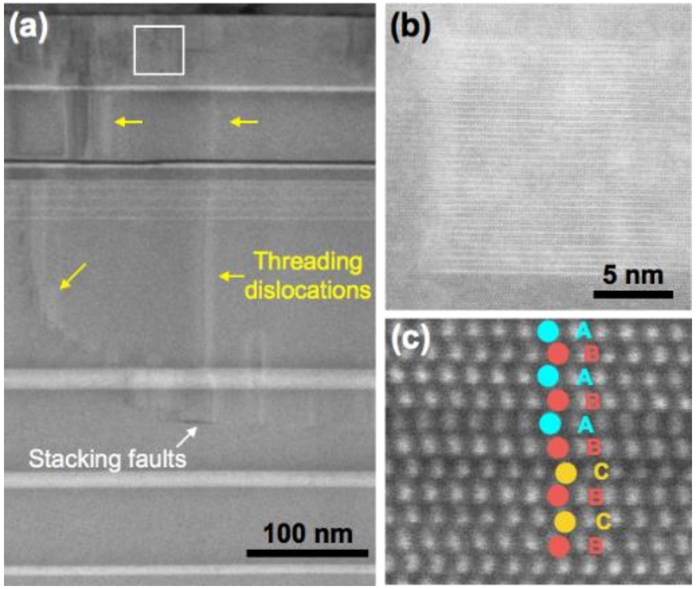
Remaining work: Path to 2x and 3x MJ-LED

Integrate TJs into MJ-LED



Chang *et al.*, IEEE JQE 51 3300505 (2015).

TEM of InGaN/GaN MQWs



- Currently developing all-MOCVD 4x MJ-LED to assess baseline performance
- Strain-induced defectivity and InGaN thermal decompositions key concerns
- Examining reduced MOCVD growth temperatures to increase thermal budget
- Monitor InGaN integrity using transmission electron microscopy (TEM)

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Thank You

Performing Organization(s)

PI Name and Title

PI Tel and/or Email

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Project Budget

Project Budget: $1,000,000 over 2 years
Variances: None.
Cost to Date: 25%.
Additional Funding: None.

Budget History					
10/1 – FY 2019		FY 2019 (current)		9/30 FY 2020 – (planned)	
DOE	Cost-share	DOE	Cost-share	DOE	Cost-share
$1,000,000	0	$500,000	0	$500,000	0

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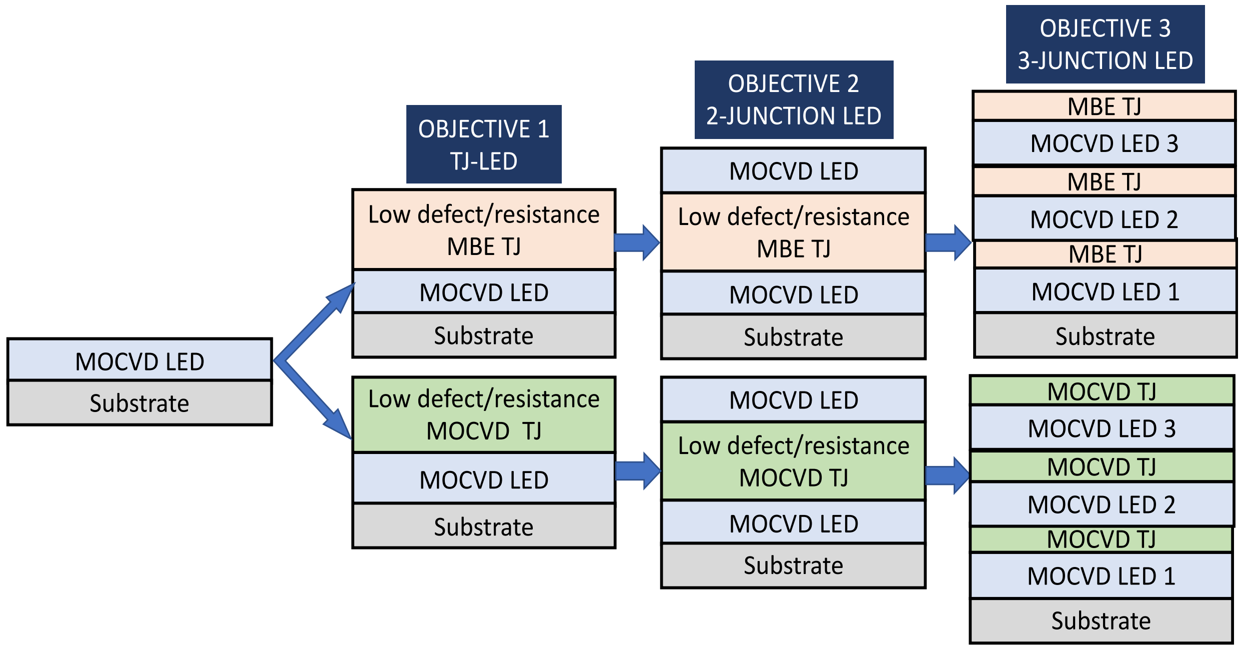
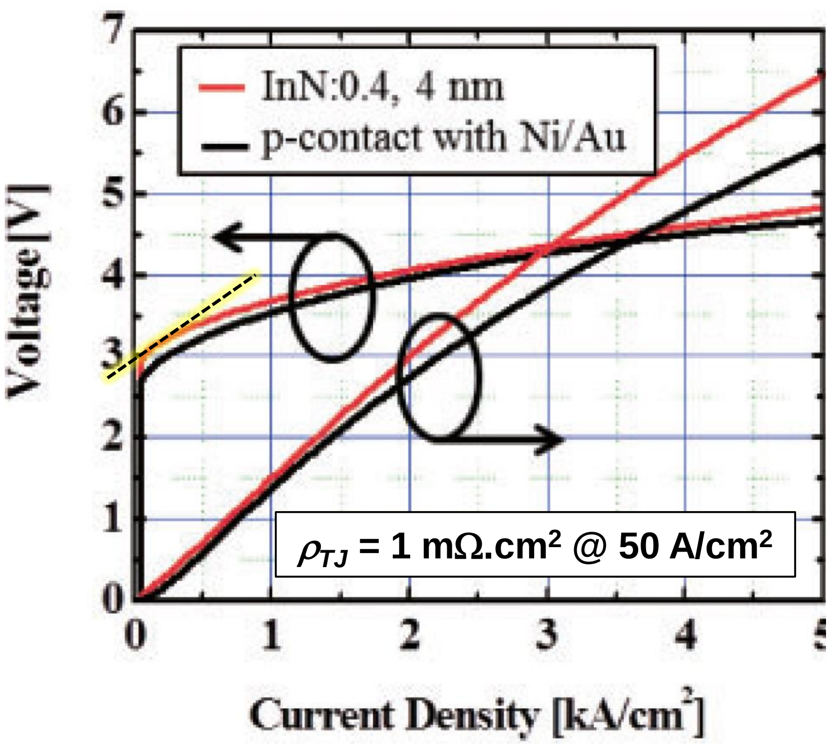
Project Plan and Schedule

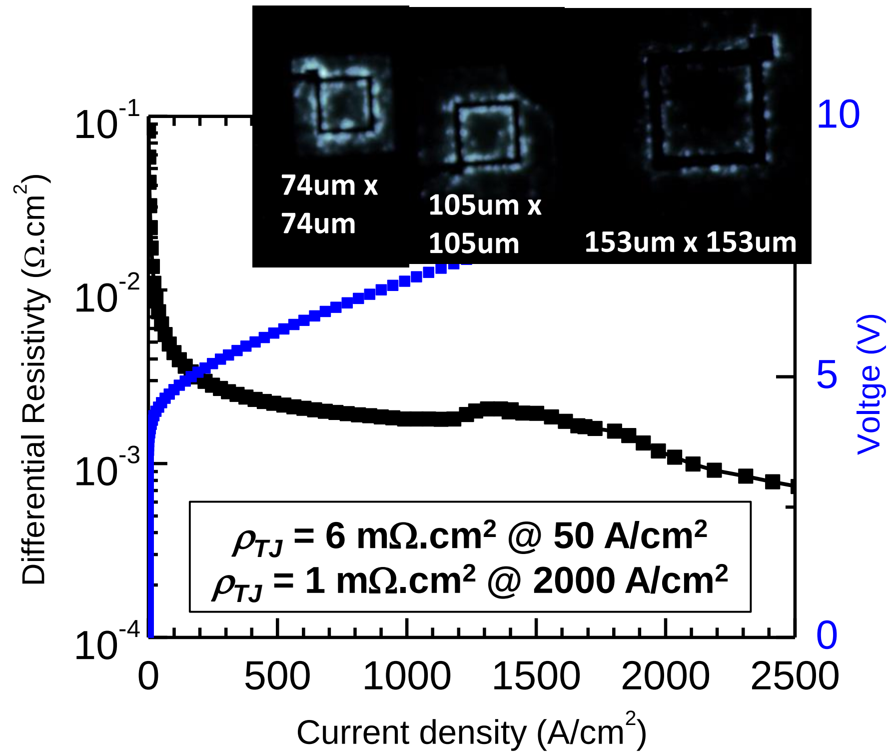


1. Demonstrate TJ on MOCVD LED; 7/2019
    1. TJ with resistivity < 1 mΩ.cm2
    2. Baseline 4x MJ-LED
    3. TJ-LED with EQE > 0.2 and WPE > 0.18 at Jabs = 35A/cm2
2. Demonstrate 2x TJ-LED; 3/2020
    1. 2xMJ-LED with EQE > 0.4 and WPE > 0.18 operating at Jeff = 70 A/cm2
3. Demonstrate droop-free 3xMJ-LED; 9/2020
    1. 3xMJ-LED with < 0.1 excess turn-on voltage
    2. 3xMJ-LED with EQE > 0.6 and WPE > 0.18 operating at Jeff = 100 A/cm2
4. External validation of MJ-LED performance; 9/2020

References



Electroluminescence and *IV*



- Polarization doping with InGaN interlayer reduces rTJ
- Best results reported have high In content that is optically absorbing
- High In content also reduces thermal budget

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